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Vibrating nonlocal multi-nanoplate system under inplane magnetic field

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The recent development in nanotechnology resulted in growing of various nanoplate like structures. High attention was devoted to graphene sheet nanostructure, which enforced the scientist to start developing various theoretical models to investigate its physical properties. Magnetic field effects on nanoplates, especially graphene sheets, have also attracted a considerable attention of the scientific community. Here, by using the nonlocal theory, we examine the influence of in-plane magnetic field on the viscoelastic orthotropic multi-nanoplate system (VOMNPS) embedded in a viscoelastic medium. We derive the system of m partial differential equations describing the free transverse vibration of VOMNPS under the uniaxial in-plane magnetic field using the Eringen's nonlocal elasticity and Kirchhoff's plate theory considering the viscoelastic and orthotropic material properties of nanoplates. Closed form solutions for complex natural frequencies are derived by applying the Navier's and trigonometric method for the case of simply supported nanoplates. The results obtained with analytical method are validated with the results obtained by using the numerical method. In addition, numerical examples are given to show the effects of nonlocal parameter, internal damping, damping and stiffness of viscoelastic medium, rotary inertia and uniaxial in-plane magnetic force on the real and the imaginary parts of complex natural frequencies of VOMNPS. This study can be useful as a starting point for the research and design of nanoelectromechanical devices based on graphene sheets.

1. Introduction

Complex nanoscale systems are made of nanostructures with superior thermal, electric, mechanical, magnetic and other physical properties (Hao et al., 2011; Qian et al., 2000; Loomis and Panchapakesan, 2012; Grimes et al., 2000; Sandler et al., 1999) that makes them convenient for potential application in nanoelectromechanical systems (NEMS) and micro-electromechanical systems (MEMS) (Loomis et al., 2012a, 2013; Lu and Panchapakesan, 2007a; Lu and Panchapakesan, 2007b; Bunch et al., 2007; Liu et al., 2011). Nanoplate-like nanostructures can be synthetized from different materials to make gold nanoplates, silver nanoplates, boron-nitride sheets, ZnO nanoplates, graphene sheets (Loomis et al., 2012b; Liu et al., 2012; Golberg et al., 2010; Zhang and Huang, 2006; Arani et al., 2014; Meyer et al., 2007; Ramanathan et al., 2008). Studying the vibration behavior of such nanoscale structures may be important step for their optimal application in nanoengineering.

Under complex nanostructure systems we usually mean on nanoscale systems composed of multiple nanorods, nanobeams or nanoplates embedded in certain type of medium. Special class of these systems is multi-nanoplate like system such as multi-layered graphene sheets bonded with certain type of medium. Different studies and research methodologies applied to such systems are presented in the literature by different authors (Stankovich et al., 2006; Shahil and Balandin, 2012; Li et al., 2010; Ansari et al., 2011; Pumera et al., 2010; Lin, 2015; Lin, 2012). In theoretical continuum models of graphene sheets, they are observed as both, isotropic and orthotropic materials. Behfar et al (Behfar and Naghdabadi, 2005). analyzed the vibration behavior of multi-layered graphene sheets system as an orthotropic multi-nanoplate system embedded in elastic medium, where natural

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frequencies and corresponding modes are found. Arghavan (2012) performed an extensive study on mechanical properties and vibration behavior of graphene sheets also using an orthotropic continuum plate theory to model observed nanostructures. Further, Pradhan et al (Pradhan and Kumar, 2011). employed numerical differential quadrature method to study the vibration of single layered graphene sheets using the nonlocal orthotropic plate theory. Finally, Bu et al (Ni et al., 2010). observed graphene sheets as anisotropic structures and concluded that such properties are attributed to the hexagonal structure of graphene unit cells. They performed molecular dynamics simulations and demonstrated different fractures in longitudinal and transverse modes. However, under certain assumptions and for specific applications, graphene sheets can be observed as isotropic nanoplate structures (Pradhan and Phadikar, 2009; Liang and Han, 2014; Singh and Patel, 2016; Ansari et al., 2010; Murmu and Adhikari, 2011). In this paper, we adopted an orthotropic nonlocal plate theory to model graphene sheets.

When magnetic field is exerted on a conducting nanoplate structure, it can exhibit various dynamical behaviors depending of the magnitude of the field, magnetic permeability of the continuum and deformation regime. Vibration response of carbon nanotubes (CNTs) in the presence of magnetic field is widely examined by many investigators. Murmu et al. (2012a). examined the vibration behavior of a double-walled carbon nanotube subjected to an externally applied longitudinal magnetic field. Based on the nonlocal elasticity theory, Euler–Bernoulli beam model and Maxwell's classical relations, the authors derived a set of two governing equations for transverse vibration of a double walled CNT system. By using the method of separation of variables, they obtained analytical solution for transverse displacements, natural frequencies and amplitude ratios. They have shown that the applied longitudinal magnetic field has a strong influence on the dynamic behavior of a double-walled CNT system. In (Murmu et al., 2012b), the same authors presented a mechanical model of two single-walled CNTs coupled with elastic medium and influenced by the longitudinal magnetic field. They derived governing equations for the free vibrations and analytically obtained nonlocal natural frequencies of the system using the Eringen's nonlocal elasticity theory, Euler–Bernoulli beam model and Maxwell's relations. Kiani (2014a) analyzed the vibration and instability behavior of a single-walled CNT under a general magnetic field. By using the nonlocal Rayleigh beam theory and Maxwell's relations, the dimensionless governing equation for the free vibration of the system is derived considering a general magnetic field. The longitudinal and flexural frequencies are obtained analytically and effects of the longitudinal and transverse magnetic fields are shown through several numerical examples. Further, Narendar et al. (2012). studied the wave propagation in a single-walled CNT under longitudinal magnetic field. The authors derived nonlocal governing differential equation considering the Maxwell's equations, nonlocal elasticity theory and Euler–Bernoulli beam model. The wave propagation analysis is performed using the spectral analysis. It is found that nonlocal effects reduces the wave velocity irrespective of the presence of a magnetic field and doesn't have an influence on it in the higher frequency region. Recently, several theoretical studies of nanoplates under the influence of magnetic field are performed. Murmu et al. (2013). studied the transverse vibration of a single-layer graphene sheet (SLGS) embedded in elastic medium and under the influence of in-plane magnetic field by using the nonlocal theory. The authors have examined the effects of nonlocal parameter and in-plane magnetic field on natural frequencies for different aspect ratios of SLGS. Explicit expressions for natural frequencies were derived analytically. Ghorbanpour Arani et al. (2013). investigated the influence of in-plane two-dimensional magnetic field and biaxial preload on vibration of a double orthotropic graphene sheet system coupled with Pasternak type of elastic layer. The thermo-nonlocal elasticity theory and Maxwell's relations are used to derive governing equations of the system. In addition, the differential quadrature method (DQM) is employed in order to solve the equations. The effects of magnetic field, in-plane preload, nonlocal parameter and different aspect ratios on frequencies of graphene sheets were examined. The free in-plane and out-of-plane vibration study of a rectangular nanoplate under the influence of unidirectional in-plane magnetic field was conducted by Kiani (2014b). The authors employed Kirchhoff, Mindlin and higher order plate theories using the nonlocal elasticity theory. The effects of small-scale parameter, magnetic field and aspect ratios on natural frequencies of the in-plane and out-of-plane vibrations were investigated. The reason for different properties and dynamic behavior of nanostructures in the presence of magnetic field is due to acting electromagnetic forces on each element of a structure. It should be noted that by considering the Maxwell's equations and Lorentz's forces, one could form relations between forces acting on each particle of a nanostructure and vector magnetic field.

Until now, there is no experimental work reported in the literature regarding to the vibration behavior of multi-nano-beam/plates system under the influence of magnetic field. Nevertheless, some experiments have shown that certain physical and mechanical properties are changing and some specific phenomena's appears in CNTs and graphene sheets when a magnetic field is applied on them (Camponeschi et al., 2007; Kiani, 2014c; Fujiwara et al., 2001; Peng, 2011; Shizuya, 2007; Fu et al., 2011; Lopez-Urias et al., 2006; Faugeras et al., 2010; Kan et al., 2008; Nair et al., 2013; Ning et al., 2013; Olsen et al., 2013; Pesin and MacDonald, 2012; Yazyev, 2010; Wang et al., 2009). In addition, there are some reports (Garmestani et al., 2003; Ahir et al., 2008; Kimura et al., 2002) about the alignment of carbon nanotubes (CNTs) when magnetic field is exerted on arbitrary placed ensembles of CNTs. In general, it is not an easy task to perform experiments on nanoscale level owing to the weak control of parameters. Atomistic simulation methods can be very efficient for the investigation of the mechanical behavior of nanostructures. However, such methods are computationally prohibitive for complex nanoscale systems since a large number of atoms need to be considered in the simulations. Finally, continuum based methods seems to be a logical tool utilized in the theoretical investigation of the mechanical behavior of complex nanostructure systems. Nevertheless, classical continuum theory neglects the interatomic interactions and thus, it needs to be modified to consider such effects. Such modifications were conducted by Kröner (1967) and Eringen (1972) using the integral forms in the stress-strain relation. Here, we will utilize the Eringen nonlocal differential form of equation (Eringen, 1983), which accounts for the small-size effects trough a single parameter. In the literature, there are numerous of studies on vibration behavior of nanostructures using the nonlocal theory (Peddieson et al., 2003; Wang and Liew, 2007; Murmu and Adhikari, 2010; Reddy, 2007; Huu-Tai, 2012; Wang et al., 2011; Arash and Wang, 2014; Malekzadeh and Shojaee, 2013; Mohammadi et al., 2013).

By browsing the literature, it is found that the free vibration problem of a multiple-nanostructure system is analytically treated in a small number of papers. The presented dynamical model of a multiple graphene sheets system can be important step in design of complex NEMS devices and nanocomposites, so this paper aims to fill the gap by providing the analytical results for futures studies in nanoengineering practice. In the following, we utilize the nonlocal theory to investigate the free vibration behavior of VOMNPS embedded in a viscoelastic medium and subjected to the in-plane magnetic field. For the mechanical model of a graphene sheet, we